Information Theory: New Challenges and New Interdisciplinary Tools

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1 Background

Information Theory (IT) is concerned with identifying, characterization and computation of basic limits of performance measures of communication systems. The classical question that it seeks to answer is what are the information rates in the multi-user setting that can be transmitted reliably over a given noisy channel. The transmission may involve various transmitter and various receivers. Rendering transmission over noisy channels reliable involves coding of the information to be transmitted. A given transmission rate vector C is said to be reliable if for any rate $C' < C$ and every $\epsilon > 0$ there exists a code that allows transmission at the rate C' with error rates smaller than ϵ. The set of reliable transmission rates C are called the capacity region.

In this proposal we seek to create cooperation between specialists on classical information theory (IT) and other disciplines that are needed for the computations of new concepts of capacity that appear in the next generation networks in which the geometric aspects, mobility, power restriction play a key role on the capacity and connectivity. In view of the wealth of mathematical tools that are needed to study networks (and in particular SNs), we present a proposal for an inter-disciplinary research for networking dimensioning and design.

2 Objectives and Challenges

General reasons for creating this collaboration are as follows:

1. Collaborations within the teams of this project will provide a large added value with respect to the sum of individual research of each group separately, since at present, no partner specializes in more than one or two of the tools that we propose.

2. All participants in the proposed project are interested in learning from other participants about novel tools and/or new engineering problems in which their own tools can be used.

3. In particular, a major objective of the INRIA groups is to develop competence at INRIA in Information Theory which is crucial for understanding the limitations of cellular, sensors and ad-hoc networks and thus in the designing and dimensioning of networks.

We list the following scientific objectives and challenges for this proposal:

- Create new notions of capacity of spatial networks, by introducing the concepts of non-cooperative capacity (where cooperation is impossible due to decentralization)[1].

- We shall work on defining and characterizing the concept of worse case capacity. This will be used in adverserial contexts of
  (i) networking (intrusions and jamming)
  (ii) the watermarking problem.

- Study information theoretic limitations in the presence of malicious users, both in wireless communication as well as in the context of watermarking (which will be described in the next Section).

- Implications of information theoretical limits that will be obtained on session level performance.

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[1] the last statement refers to cooperation between mobiles and not to the cooperation between members of the ARC proposal

3 Description of tools

We describe below the main novel tools that will be used in the proposed project along with the technological context that requires these new tools. Participants of the proposed collaboration will not only use these tools but will also develop them when needed.

3.1 Spatial Networks:

In recent years we have been witnessing an impressive development and deployment of novel wireless technologies WiFi (e.g. the IEEE 802.11), WiMax (e.g. the IEEE 802.16), Ad-hoc networks, sensor networks and third generation cellular networks (e.g. UMTS). We shall call these "Spatial Networks" (SN). These networks have raised many questions involving new concepts of spatial capacities, often related to geometric nature of these networks. In particular, in these networks one is interested in characterizing the spatial density of reliable transmission rates, which are measured in terms of bits per meter per second. Other basic measures in such networks are connectivity and coverage. We call "Spatial Information Theory" (SIT) the discipline that is dedicated to the performance limits of these networks. SIT is very recent and has been using sophisticated probabilistic tools such as stochastic geometry and percolation theory.

Stochastic geometry and percolation are among the most promising tools in SIT that have been used to determine the capacity, the coverage and the connectivity of SNs. The main expertise in this area are in the TREC group at INRIA, see e.g. [12, 19, 20], as well as in EPFL [21] (These groups have already collaborated, see [18].)

Some other tools that are relevant to the area of spatial networks are:

- Random matrices (will be described below).
- Queueing theory tools, that turn out to be useful for the study of capacity, connectivity and coverage of ad-hoc and sensor networks in one dimensional case (such as communication between cars on a highway, see [17]). These tools enable to take into account not only path-loss but also fast fading shadowing and other characteristics of the radio channel. Some queueing theory techniques extend to two dimensional space, see [23].

In addition to the study of spatial aspects of SN, temporal aspects are also important in the context of the system's capacity. In networks with low connectivity, one can rely on mobility of relay nodes in order to increase connectivity. Connectivity can also be increased with larger transmission powers at the cost of increasing interferences, decreasing spatial reuse and thus a possible decrease in the system's capacity. It is therefore important to understand tradeoffs between capacity and delays. The Maestro group of INRIA [22] as well as participants from Univ. of Cyprus [11] are involved in this direction.

The collaboration between experts on more classical IT (Eurecom) and experts in SIT will allow us to include more sophisticated channel models in the analysis of SITs (such as MIMO channels, OFDM and OFDMA etc). We plan to study within the collaboration the gain in connectivity, power consumption and capacity obtained by using such channels.

3.2 Game Theory

We mention below two main directions in which game theory will be used. As part of this proposal, it is planed to extend the game theoretical tools in order to model the distributed nature of the available information and the fact that the games are often multi-objective. The objectives may include throughput maximization, as well as power and delay minimization.

Information theoretical notions of capacity related to non-cooperative games:
An important feature in classical IT paradigms related to several users is the need of cooperation in order to achieve or to approach the capacity (an example is the interference channel). Due to the decentralized and distributed nature of many SNs, one can often exclude such cooperation. In those cases, the question of the global optimal reliable transmission rate is not useful. Instead, the natural performance measure is the maximal "individual optimal" reliable transmission rate. Non-cooperative game theory is the precise framework to model this scenario and to investigate their capacity. The individual optimal reliable transmission rate is then obtained by identifying the *Nash equilibrium* which is the basic optimality notion in noncooperative game theory.

Zero-sum games:
Zero-sum games are an extreme case of non-cooperative games with two players. There is a cost function that depends on actions taken by two players; one who wish to minimize it and the other who wishes to maximize

- to the design of robust policies when there is uncertainty over some parameters that influence the cost. These parameters are then modeled as a second malicious player.
- to model actual malicious decision makers such as intruders, mobiles that aim at jamming, D's (Denial of Service) attackers etc.

3.3 Random matrix theory

Several tools from Physics have been found to be very useful for describing large systems. The theory of random matrices has been used for studying asymptotic behavior of both cellular as well as of ad-hoc networks when the number of users or the number of antennas is large.

The proposed work concerns applications of random matrix theory and unitary random matrix theory [8, 9, 10] to cellular networks. Eurecom has the main expertise in this area. Some recent collaborative research has started this year between the Maestro group (INRIA) and Eurecom, leading to the publications: [6, 7] as well as between INT and Eurecom.

Participants: Eurecom, INRIA Sophia-Antipolis GET/INT.

3.4 Analysis of optimal paths in ad-hoc networks using tools from electromagnetic fields and optics

Other tools from physics have proved to be very useful for analyzing ad-hoc and sensor networks. These include partial differential equations from electro-magnetic fields as well as differential equations arising from the description of the paths of light in optics.

4 New challenges

4.1 Intrusion detection, and detection of misbehavior

Preliminary results (INRIA Sophia-Antipolis) using zero-sum games for detection intrusion have appeared in [25]. It is planed to pursue working on this problem in order to take into account the detection time (the time needed before detecting the target).

The basic feature of attack and misbehavior strategies is that they are entirely unpredictable. In the presence of such uncertainty, it is meaningful to seek models and decision rules that are robust, namely they perform well for a wide range of uncertainty conditions. One useful design philosophy is to apply a formulation and identify the rule that optimizes worst-case performance over the class of allowed uncertainty conditions. The situation becomes more challenging by the fact that several protocols operate in a non-deterministic manner. Thus the distinction of normal behavior from occasional misbehavior is not straightforward. In a wireless network, information about the behavior of nodes can become readily available to immediate neighbors through direct observation measurements. If these measurements are compared with their counterparts for normal protocol operation, it is then contingent upon the detection rule to decide whether the protocol is normally executed or not.

Participants from the university of Thessaly propose to research ways of modeling the attack itself and the incurred benefit from the attack. Furthermore, they propose to view the detection system and the attacker as players participating in a zero-sum game. On the one hand, the detection system would like to devise a detection rule which minimizes detection time of the attacker. If a sequential detection scheme is used, this is translated to minimum number of samples in order to derive decision as to whether an attack occurs or not. On the other hand, the attacker would like to devise an attack time that will prolong detection as much as possible. Therefore, the objective function in that aspect would be the detection time.

Another aspect of the problem can consider as objective functions the percentage of accessing the channel for the attacker and the legitimate node. After addressing and studying the fundamental problem, we can view immediate extensions to that, such as operation in the presence of interference.

4.2 Optimizing Cellular Networks using random matrix theory

The increasing penetration and widespread deployment of cellular networks and wireless local area networks have fueled an explosive growth of theoretical research in information theory.

In an initial phase the main efforts have been focused on single isolated cells. Since, from an information theoretic prospective such a system is modeled as a multiple access channel in the up-link and a broadcast channel in the downlink, the multiple access and the broadcast channels have been the core topics in information theory for wireless communications. In this framework, randomly-spread DS-CDMA and OFDM systems received

special attentions due to their widespread use. Important results were obtained in [27, 28, 29, 31] for an asymptotic setup in which both the number of users and the processing gains go to infinity while their ratio tends to some finite constant (referred to as the "cell load"). Using results from the theory of random matrices, limiting analytical deterministic expressions for the spectral efficiency of CDMA systems with linear and non-linear receivers were derived for both non-fading [28] and flat fading channels [27]. Analogously, the output SINR of linear receivers for OFDM systems was determined in [31]. Although some fundamental aspects of single isolated cell systems are still unknown — the analysis of broadcast channels is very recent [30] and the general case is still unexplored, the market pressure for 4th generation wireless systems makes urgent a deep understanding of wireless systems from a global network prospective. The interest of the scientific community is addressed mainly in the following directions:

* Multi-cell systems ;
* Multi-hopping or ad-hoc networks ;
* Hybrid ad-hoc networks.

In its full generality, the information theoretic understanding of multi- cell and/or multi-hopping networks touches upon the most basic information theoretic models, not yet fully understood. Those comprise combinations of multiple-access, broadcast, interference and relay multi-input multi-output frequency selective fading channels as well as fundamental network information theory aspects. It is expected that random matrices together with information theory will play a central role in assessing the ultimate potential and limitations of multi-cell and/or multi-hopping networks as well as providing fundamental insights into the structure and operation of future generations systems. Some more specific issues in optimize cellular networks appear in the next subsections.

4.3 Power control

Novel techniques in stochastic games allow to solve decentralized power control problems in which mobiles determine their transmission power independently of each other as a function of the radio conditions of their respective channels (which is defined as a finite Markov chain). Mobiles are assume to know only their own channel state. Each mobile is assumed to have constraints on its average transmission power.

An extreme case of the non-cooperative power control is the one in which one (or more) mobile tries to jam the communications between other mobiles, or between mobiles and their base station. New tools in constrained stochastic zero-sum games have recently been developed at the Maestro team (INRIA) which allow to to identify the power control policies of mobiles which guarantee the best throughput under any strategy of the jammer, see [24].

We plan to have collaborations between the game theorists and other teams in order to further define in a more general context a "non-cooperative capacity" as well as the "worst case capacity" for various SNs. In particular, an important potential collaboration will be in applying this tool to watermarking, described in the next subsection.

Inter-cell aspects The conventional power control requires that users with smallest channel gains transmit at the largest power level to render the received power of all users constant. However, this increases the inter-cell interference with respect to the opposite strategy since the users with smallest channel gains are usually the ones at the border of the cell. Therefore, in multi-cell the optimal power allocation should result as the trade-off between the required quality of service and the inter-cell generated interference. Random matrix theory will be used for this study by the Eurecom team. The impact of the power control on session level performance will be studied the group of France Telecom.

The TREC group of INRIA works actively on Call Admission Control methods combined with power control together with FTRD [48].

4.4 Optimal base station deployment

In order to increase the network capacity in hot spots the network providers usually increase the number of cells. However, this implies an increase in inter-cell interference. The optimal base station deployment is the trade-off between the increase in capacity and the increase in inter-cell interference as additional cells are introduced in the system. The project will extend the performance analysis to hybrid ad-hoc networks. In this case the system is still structured in cells but the intra-cell communications follows the ad-hoc networks model with multi-hopping, while the inter-cell communications use the base stations as relay nodes. This scenario is the most promising for the 4th generation mobile communications since it combines the flexible deployment structure of ad hoc networks with the wide coverage and scalability of cellular networks. Additionally, as already mentioned, the results in [32] suggest the use of small ad-hoc networks. The relay capabilities of the nodes in an ad-hoc network should allow a reduction in transmitted power, thus in inter-cell interference with a consequent increase in network capacity. Analogously to the case of multi-cell networks, the project will analyze hybrid

ad-hoc networks considering also additional metrics, e.g. the maximum and average delay, which assume special relevance in multi-hopping. The optimal base station deployment and power allocation will also be studied.

4.5 Watermarking

Participants: Eurecom and INRIA (Sophia-Antipolis), IRISA (Temics)

Digital watermarking aims at hiding discrete messages into multimedia content. The watermark must not spoil the regular use of the content, i.e., the watermark should be non perceptible. Hence, the embedding is usually done in a transformed domain where a human perception model is exploited to assess the non perceptibility criterion. The watermarking problem can be regarded as a problem of creating a communication channel within the content. This channel must be secure and robust to usual content manipulations like lossy compression, filtering, geometrical transformations for images and video.

The main expertise on watermarking is within the Temics group at INRIA, see for example their publication [2] which has received the best paper award. Although the group does not wish to participate officially in the ARC, they will be happy to collaborate on this issue.

A recent and novel line of research in watermarking is to study it within an adverserial context. The extra information that is added to the original message (i.e. the watermarking) should be designed in a way that it could be recovered even in the presence of the whole multimedia content is further modified possibly by a malicious attacker. Some recent references on that are [3, 1, 4].

5 List of participants

1. **INRIA Sophia-Antipolis (Maestro group):** Eitan Altman, Philippe Nain, Nicholas Bonneau
2. **INRIA Rocquencourt (Hypercom group):** Philippe Jacquet
3. **INRIA ENS (TREC group):** Francois Baccelli, Thomas Bonald, Alexandre Proutière, Pierre Brémaud, Bartek Blaszczyszyn
4. **France-Telecom:** Thomas Bonald, Alexandre Proutière (also affiliated in INRIA ENS), Nidhi Hegde.
5. **IRISA, (Projet Armor):** Bruno Tuffin, David Ros.
   The **Temics group of IRISA** is also interested to collaborate, but do not wish to commit themselves to this ARC. The potential interested persons in Temics are Christine Guillemot, Francois Cayre, Teddy Furon, Caroline Furon.
6. **EURECOM:** Merouane Debbah (Mobile Communication Group)
7. **EPFL:** Patrick Thiran as well as the following members of his group: Dr Oliver Dousse, Mathilde Durvy, Dr Can Emre Koksal. In addition
8. **Univ of Cyprus, School of Engineering:** Stavros Toumpis and C. D. Charalambous.
9. **Univ. of Thessaly, Volos, Greece:** Leandros Tassiulas
10. **GET/INT:** Tijani Chahed, Mariana Dirani.

6 Role of the participants

Game Theory. The participants from the Armor group of IRISA (Bruno Tuffin and David Ros), and Eitan Altman from the Maestro (INRIA) have long been working on game theoretic models to describe and analyse both cooperative as well as non-cooperative behavior in networking. These participants are specialists both in networking as well as in game theory and have contributed to developing tools in both areas. Other participants in this area are Philippe Nain from Maestro and the group from Univ. of Thessaly.

The above participants will collaborate with the participants specialized in both IT techniques (Eurecom and Temics project) as well as with those specialized in SN. The session level impact will be carried in collaboration with the participants of FTRD and INT.

Random matrices

The participants are Merouane Debbah (Eurecom) and the Maestro group of INRIA. Moreover, members from INT are currently collaborating with Eurecom on the use of random matrices in capacity calculations in the downlink of UMTS systems

Analysis of optimal paths in ad-hoc networks using tools from electromagnetic fields and optics
The participants from Univ. of Cyprus as well as from Univ. of Thessaly (Greece) are in the origin of the use of partial differential equations from electro-magnetic fields to describe and analyse routing along optimal paths in massively dense sensor networks and ad-hoc networks [13, 14].

Philippe Jacquet from the Hypercom group of INRIA is the origin of the use of differential equations used in optics for static ad-hoc networks [15].

Spatial Information Theory (SIT) and Spatial Networks (SN)
Participants in these areas are

- The TREC group of INRIA (which has been developing powerful stochastic geometry tools for the last ten years and applying them to SNs and SIT),
- EPFL: will bring the expertise on SNs and SIT using percolation theory.
- Eurecom, who will contribute to SIT and SN using their expertise in space-time coding, and random matrices, as well as classical Information Theory,
- Univ. of Cyprus and the Maestro group of INRIA who have worked on temporal aspects of SN.

Session level implications. Will be studied by FTRD group (see [34, 35, 36, 37] for their previous related work) and by the group of GET/INT.

Watermarking Will be investigated by INRIA Sophia-Antipolis, and by Eurecom. They will collaborate with the Temics group (IRISA) who is interested in this collaboration but do not wish to be officially part of this ARC.

7 Requested budget

The following items are requested:

1. 10 months of a postdoc each year: 30.7 K Euros per year.
2. 10 K Euros per year for both travel money as well as local expenses to finance mutual visits,
3. 6 K Euros per year for organizing a yearly workshop for all participants.
4. 2 interns (such as summer internships of Ph.D. students): 9 K Euros.

This gives a total of 55.7 K-Euros per year.

If possible, we wish each postdoc to spend half of his time with one of the INRIA groups and the rest at one of the non-INRIA collaborators. If it is not possible, then we would like each postdoc to have several trips to other groups.

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8 Appendix: More details on some of the groups

8.1 Armor group, IRISA

Armor project-team has recently been active on non-cooperative game theory through the study of pricing schemes in telecommunication networks. The basic idea is to investigate and control the interactions of selfish users by proposing different forms of service differentiation. This has been done through second price auctions [40, 38] or multiple classes with static pricing [39] for instance. Some specificities of of the underlying networks are used, such as the modeling of TCP/IP [43], the active queue management (AQM) algorithms developed in the literature [42], or the interferences in CDMA networks [41]. The resulting Nash equilibria are derived, and, in most cases, parameters optimizing the revenue or social welfare were found.

Members of the project aim at extending this activity on non-cooperative game theory to other fields. This proposal is a good candidate towards this goal.

8.2 University of Thessaly expertise

The main areas of research of the participants form the university of Thessaly are:

- o Cross-layer design, physical to network
- o Sensor networks : monitoring and information collection modeling
- o Intrusion and misbehavior detection in wireless networks
- o Peer to peer networking
- o Network control and QoS delivery
- o Energy-efficient communication
- o Resilient ad-hoc networking

8.3 Group from GET/INT

Participants from INT have been active on modeling and analysis of SNs, especially cellular ones. Their works cover issues such as QoS via admission control in CDMA-based UMTS systems, including the impact of mobility (see [44]) as well as the performance of TCP in the presence of errors in the wireless links. They are currently considering the integration of IT in the calculation of capacity in SNs via a cross layer approach as well as the use of game theory in resource allocation in heterogeneous SNs.

8.4 Hypercom group of Rocquencourt

The Hypercom project is willing to contribute to this area where the challenges are very important. Philippe Jacquet, the leader of the group, has participated in a NSF panel in Chicago in 2003 about the interaction between computer science and information theory. We have proposed to introduce the concept of space and time in information theory. (also presented in ITW 2004 in San Antonio). Indeed mobile ad hoc networks carry two paradoxes related to space and time and information theory that have created a lot of feedback in the information theory community:

1. the space capacity paradox: Gupta and Kumar have shown in 1999 that the total capacity of a multihop wireless network increases when the number of nodes increases (the increase is in square root of the network size) by adding area to the network. This is a completely new paradigm in multiple access telecommunication.

2. the time capacity paradox: Grossglauser and Tse have shown in 2002 that the capacity of a randomly mobile ad-hoc network can also increase when mobile relays store packets instead of immediately retransmit them. Therefore adding more mobility to nodes increases capacity. This is also completely new in telecommunication since link capacity is not supposed to increase when we augment packet.

8.5 The EPFL group

We are applying percolation theory to derive scaling laws of large wireless multi-hop networks, in particular for connectivity and transport capacity. We are also looking at the spatial reuse that can be obtained using decentralized medium access control schemes.

(i) Connectivity: We have extended the classical Boolean model to a more realistic model (the "physical model") where two nodes are connected to each other if and only if the signal to noise ratio at the receiver (noise is here the sum of a background noise, and of the interference contributions from neighboring nodes) is larger than some prescribed value [18]. We found that the network can still have a giant connected cluster that includes most nodes despite interferences. We are currently working out the conditions for this result to hold. Wireless channels are strongly time-varying, and the impact on the connectivity of the network should be evaluated too.

(ii) Transport capacity: In their seminal paper, Gupta and Kumar gave bounds on the transport capacity of large wireless multi-hop networks. They found bounds on the actual throughput that each node experiences, when the number of nodes becomes large. We have recovered and improved these bounds using stochastic geometry and percolation theory [45, 46], and we are working on the extension on these results under various scenarios. A particular challenge is to tighten the bounds. We also want to evaluate the impact of time-variability of the wireless channels on the throughput that can be reached.

(iii) The maximal capacity of ad hoc networks is achievable by centralized scheduling schemes, which are optimized to yield the highest possible capacity. In practice, this scheduling needs to be distributed among the nodes. Many Medium Access Control (MAC) schemes have been designed to coordinate the access of network stations to the wireless medium. We want to only consider decentralized MAC algorithms, as they would otherwise not be suitable for ad hoc networks. We want to evaluate the factors that influence the performance, and more specifically, the degree of spatial reuse achieved by decentralized MAC protocols. This will lead us to design new self-organizing protocols for multi-hop ad hoc networks with high traffic load (such as [47]).

8.6 TREC

TREC (INRIA-ENS) is actively working on the development of mathematical tools combining information theoretic constraints and spatial modeling. A survey on the matter can be found at http://www.di.ens.fr/ mistral/sg/